Evaluation of Corrosion Fatigue Behaviour of Laser-welded NiTi Alloys using Bending Rotation Fatigue Test in Simulated Body Fluid

EVALUATION OF CORROSION FATIGUE BEHAVIOUR OF LASER-WELDED NITI ALLOYS USING BENDING ROTATION FATIGUE TEST IN SIMULATED BODY FLUID

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ABSTRACT

Corrosion fatigue is a process which is a consequence of synergistic interactions among the material microstructure, environment and cyclic loads/strains. This study reveals a comparison of corrosion fatigue behaviour of laser-welded and bare NiTi wires using bending rotation fatigue (BRF) test coupled with a specifically designed corrosion cell. The testing environment was Hanks' solution (simulated body fluid) at 37.5 ^oC. Electrochemical impedance spectroscopy (EIS) measurement was carried out to monitor the change of corrosion resistance of sample during the BRF test at different periods of time. Experiments indicate that the laser-welded NiTi wire would be more susceptible to the corrosion fatigue attack than the bare NiTi wire. This study can serve as a benchmark for the product designers and engineers to understand the corrosion fatigue behaviour of the NiTi laser weld joint and determine the fatigue life safety factor for the NiTi medical implants which involve laser welding in the fabrication process.

Introduction

Shape memory NiTi alloys have been extensively used for medical device applications on account of their unique shape memory effect (SME) and super-elasticity (SE), as well as good biocompatibility. Laser welding is one of the effective methods to fabricate medical implants which involve complex-shaped NiTi components. It is postulate that NiTi laser-weld joint is susceptible to corrosion fatigue attack in human body given the presence of thermally-induced defects. However, a specific study on investigating the corrosion fatigue behaviour of the NiTi laser-weld joint is still lacking in literature, and accordingly this becomes the motivation of this study.

Methodology

Fibre Laser Welding

Material used was commercial Ti-55.91 wt% NiTi wire with diameter 0.5 mm (procured form Johnson Matthey Noble Metals). The laser-welded sample was prepared by laser joining two NiTi wires using a 100 Watt CW fibre laser (Model SP-100C-0013, output wavelength 1091 nm, in-focus spot size 46 μm).

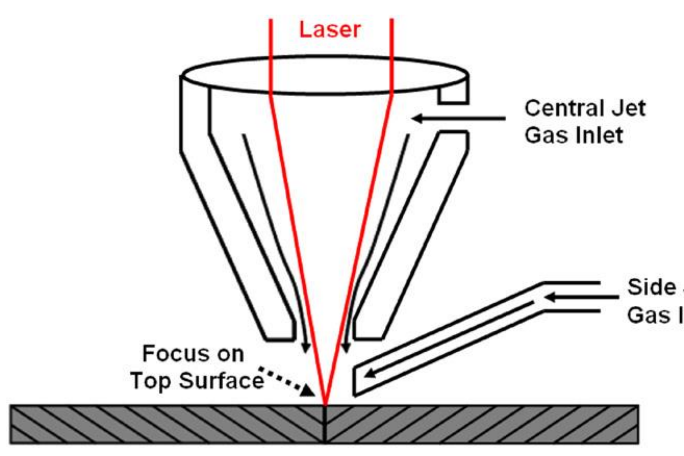

Fig. 1. Experimental setup for the fiber laser welding [1]

Table 1. Laser Welding Parameters

Laser Power	Welding Time	Focus Position	Shielding Gas
72 W	115 ms	on the Surface (+ 0 mm Defocusing)	Argon (Flow Rate: 25 L/min)

Corrosion Fatigue Testing

Fatigue life of the sample was measured by using a specifically designed test rig based on the concept of bending rotation fatigue (BRF) test [2, 3]. In the BRF test, the wire sample was bent into a semicircle (R = 60 mm) and rotated with a selected rotational speed (100 rpm or 1.67 Hz). The surface strain at the outer surface of the mid-point was given by $\varepsilon_a = d/2R$, where d is the wire diameter and R is the radius of the semicircle. The ε_a was 0.42 % in the BRF test.

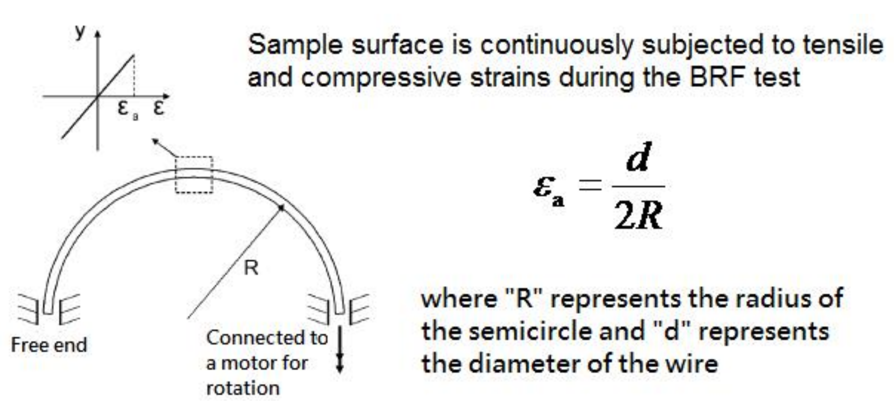

Fig. 2. Schematic diagram to illustrate the concept of bending rotation fatigue (BRF) test

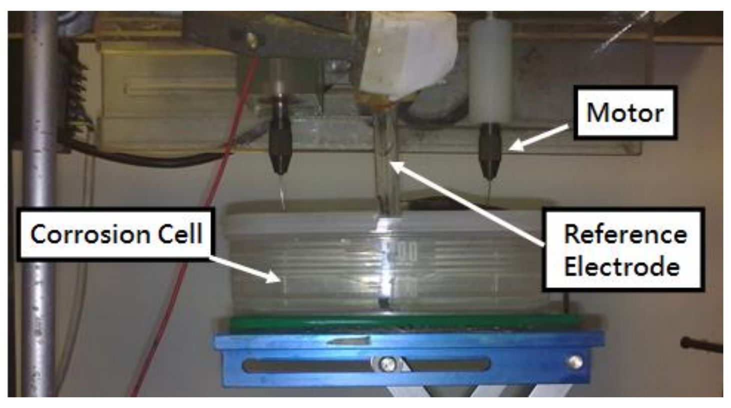

Fig. 3. Experimental setup for the corrosion fatigue test

To mimic the human body conditions, the sample was immersed in a corrosion cell which was filled with 250 mL of Hanks' solution kept at a fixed temperature of 37.5 ^oC throughout the BRF test. The surface area exposed to Hanks' solution was 0.5 cm^2. The corrosion cell was connected with the PAR 273A potentiostat for electrochemical measurement. A standard calomel electrode (SCE) was used as the reference electrode.

Table 2. Compositions of Hanks' Solution

NaCl	Na_2HPO_4	$NaHCO_3$	KCl	KH_2PO_4	$MgCl_2$-6H_2O	$MgSO_4$-7H_2O	$CaCl_2$	Glucose	pH
8 g/L	0.0475 g/L	0.35 g/L	0.4 g/L	0.06 g/L	0.10 g/L	0.10 g/L	0.18 g/L	1 g/L	7.4

Corrosion resistance of the sample during the BRF test at different periods of time (6, 24 and 48 hours) was evaluated by electrochemical impedance spectroscopy (EIS). In the EIS measurement, a sine wave of 10 mV in amplitude was applied to the sample at open-circuit potential (OCP) at 37.5 ^oC. The impedance spectra were acquired in the frequency range from 100 kHz to 1 mHz.

Results and Discussion

Fatigue Life Measurement

Both the bare and laser-welded samples showed reduction in the fatigue life when testing in Hanks' solution. However, the laser-welded sample showed a more significant degradation (42 % reduction) as compared to that of the bare sample (18 % reduction).

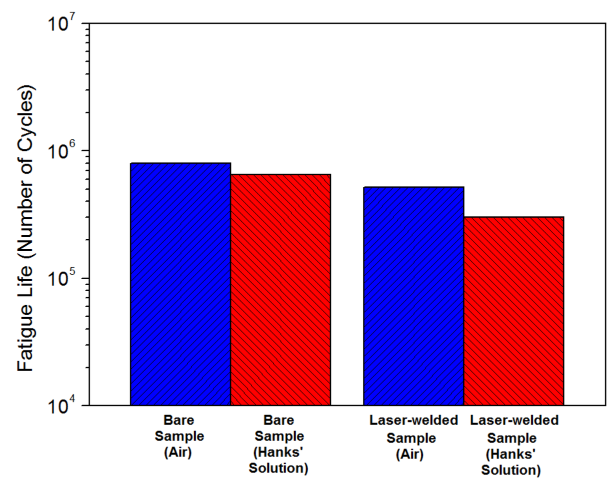

Fig. 4. Fatigue life measurement for bare and laser-welded samples after BRF tests under different conditions: air and Hanks' solution

EIS Measurement

Diameter of semicircle arc in the Nyquist plots indicates the polarization resistance (R_p), i.e. the higher the diameter, the higher is the R_p. The R_p of laser-welded sample noticeably decreased with increasing testing time, whilst decrease of R_p was also observed in the bare sample, but the magnitude was much smaller.

Presence of a single peak in the Bode plots suggests that the passive films on both the bare and laser-welded samples exhibited one relaxation time constant.

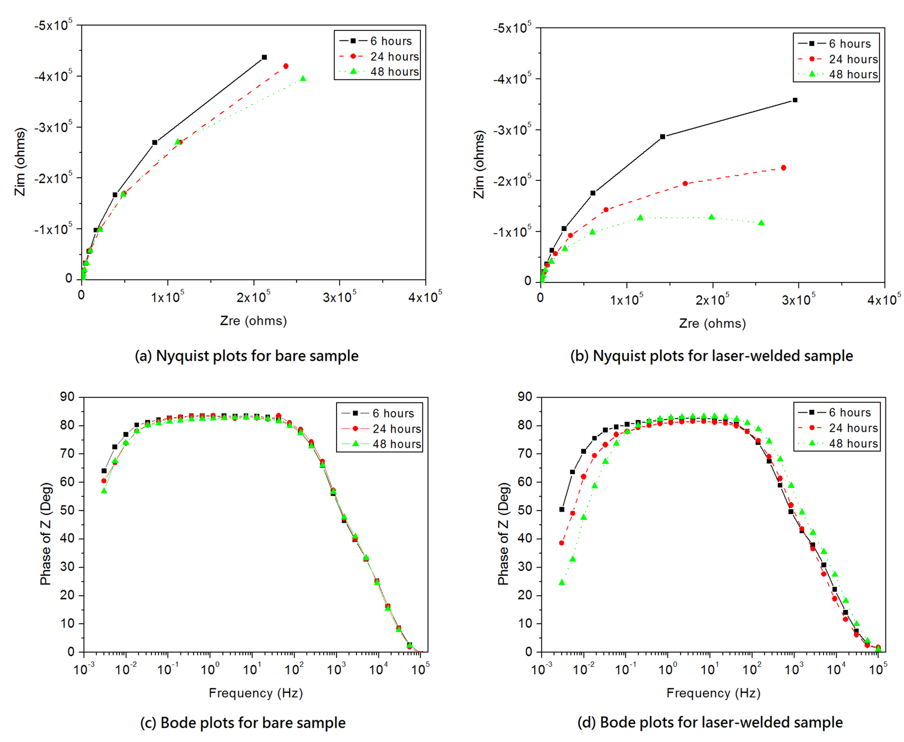

Fig. 5. EIS results: (a-b) Nyquist plots and (c-d) Bode plots for bare and laser-welded samples during BRF tests at different periods of time

SEM Fractography

Fatigue striations, a typical feature of fatigue damage, can be observed on the fracture surface of the laser-welded sample. Fracture occurred in the weld zone (WZ). Clear micro-cracks appeared on the fracture surface. Such micro-cracks were believed to be associating with hydrogen embrittlement, as there is no signs of anodic dissolution.

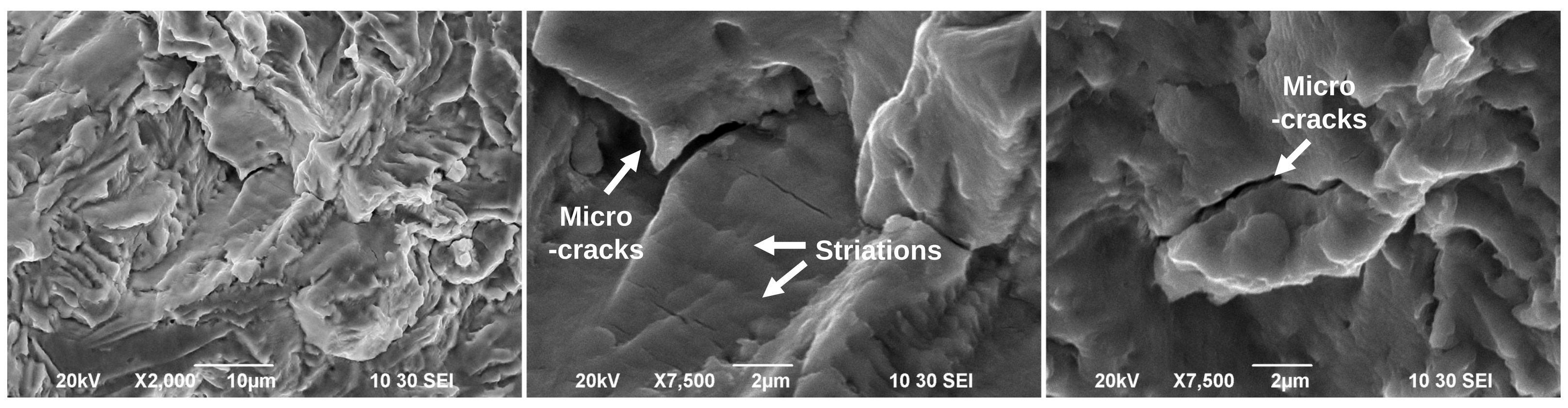

Fig. 6. SEM fractographs for the laser-welded sample after BRF test in Hanks' solution at OCP

Hydrogen Effect

In aqueous media, hydrogen can be introduced into the WZ by dissociation of hydrogen molecules into atomic hydrogen, resulting damage to the mechanical properties of the WZ, i.e. by decohesion of atomic bonds or generation of large internal pressure.

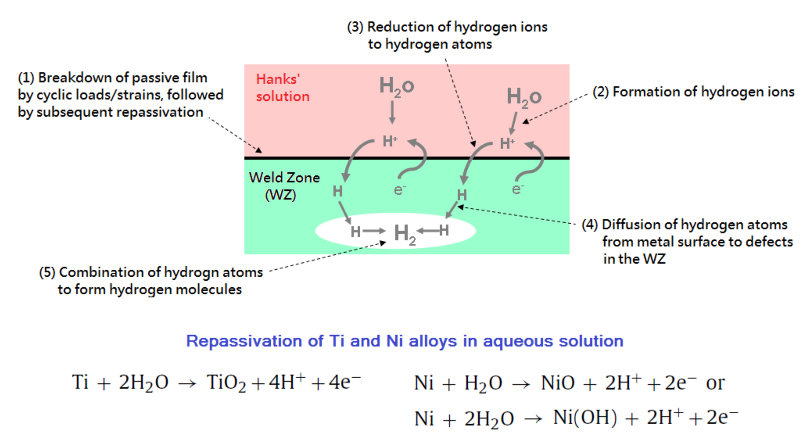

Fig. 7. Schematic diagram to illustrate the concept of hydrogen embrittlement

Conclusion

Experimental results in this study showed that the NiTi weld joint was susceptible to hydrogen attack in Hanks' solution at OCP at 37.5 ^oC, resulting in noticeable reduction in fatigue life. Fracture occurred in the weld zone (WZ), possibly due to presence of weld defects and imperfections which act as hydrogen trapping sites.

References: [1] C.W. Chan, H.C. Man, and F.T. Cheng, Mater. Sci. Eng. A 559 (2013) 407-415. [2] T. Sawaguchi, G. Kaustrater, A. Yawny, M. Wagner, and G. Eggeler, Metall. Mater. Trans., A 34 (2003) 2847-2589. [3] G. Eggeler, E. Hornbogen, A. Yawny, A. Heckmann, and M. Wagner, Mater. Sci. Eng. A 378 (2004) 24-33.